THE COMPUTER ANALYSIS OF THE HEAT EXCHANGER OF DRIVE STIRLINGA WITH THE NONSTEADY PULSING STREAM OF THE HEAT TRANSFER MEDIUM

Prof. Hab.Dr. Eng, Ushakov V., Dr.sc.ing, Blumbergs I.,
Aeronautical Institute of Riga Technical University,
1 Kalku Str., Riga, Lv-1658, Latvia

Abstract: Numerically investigated features of gas - thermodynamic parameters of recuperative type heat exchangers for cooling and heating of pulsing flow of air – working fluid of researched model of Stirling engine. Three-dimensional numerical analysis has been performed by means of CAE program Cosmos FloWorks using numerical geometric model of engine which was built in the CAD program SolidWorks. It is proved that using of pulsing flow instead of stationary flow allows reduction of dimensions of the heat exchanger. There were considered various versions of designs of heat exchangers and features of methodology of their numerical calculation.
KEYWORDS: STIRLING ENGINE, RECUPERATIVE HEAT EXCHANGER, PULSATING FLOW, COMPUTER SIMULATION NUMERICAL COMPUTATION.

1. Introduction

Stirling engine [1] is an piston engine of external combustion, which is a closed installation and allows to use any source of heat. Heat exchangers in Stirling engines largely determine overall design excellence. In the heater of working fluid the transmission of heat thermal transmission (heat transfer) from the combustion residue is carried out mainly as a result of convection of heat transfer on either side of heat-exchange surfaces, usually made as a row of smooth or ribbed tubes. For cooling of working fluid in the gas coolers usually is used water. The surface of the gas cooler considerably anymore surface of the heater because of a small difference of temperatures of coolants. Stirling engines of classical scheme [1, 2] contain regenerator, whose function is alternate capture and return of part of heat energy produced during each engine cycle. To create a gas flows of working medium in Stirling engine is used a change of physical volumes of hot and cold working piston chambers. As a result, the gas flow which is circulating in the engine is unsteady and pulsating. Conversion of thermal energy into mechanical energy is a result of compression of fixed amount of the working fluid under (at a) low temperature and following after the period of heating its expansion under high temperature. Thus, principle of operation of Stirling engine is the alternate heating and cooling of circulating in an isolated space pulsating flow of working fluid.

In this work are analyzed the heat exchangers for one-cylinder engine of of unilateral action with working and displacer pistons (β type). Unlike classical engine Stirling investigated heat exchanger is not regenerative, but recuperative, that is it not predesigned for alternate accumulation and returning of thermal energy received during each cycle of the engine [3]. Construction features [3] allow separation of flows of the working fluid: gas flow in the heater only heats up and in the cooler cools down. The proposed solution allows to obtain higher power of engine at an equal volume of the cylinder.

The purpose of the given work - development of a technique of computer modelling and the numerical analysis of features of gas-thermodynamic parameters of computer models of heat-exchangers Stirling´s engine with a pulsing flow of a working fluid with the purpose of their optimization

2. *Prerequisites and means for solving the problem*

Typical problems in the field of research recuperative heat exchangers there are: optimization of geometrical sizes heat exchanger´s (including edges, grooves, holes, etc.), a need of account of pulsations of pressure, density and the mass flow rate to allow for a relatively high speed of machine's revolutions; an estimation of opportunities of use of quasi-stationary models, etc.

The disadvantage of known analytical and numerical methods for calculation of individual components and the engine as a whole is a significant difference of used in the calculation of ideal working cycles from the working cycle of the real Stirling engine. Numerical calculation methods common generaly are used for acceleration of calculation process at the optimization of engine's parameters, whose computational model is based on any analytical model with an idealized working cycle.

This paper debate the gas-thermodynamic parameters of three-dimensional geometric computer models of heat exchangers of Stirling engine with non-stationary pulsating flow of working fluid.

Computer simulation of heat exchangers is carried out using the package of CAD/CAE software SolidWorks and Cosmos FloWorks [4]. Gas-thermodynamic parameters of the task are described by the unsteady Navier - Stokes equations with additional equations which take into account laminar or turbulent transfer. For the numerical solution in the CAE program Cosmos FloWorks is used three-dimensional geometric computer model which was created in a CAD program SolidWorks. Original mathematical model is discretized in three-dimensional space (in the computational domain), and as well in the time. For discretization of differential equations and digitally solution of algebraic equations in the program Cosmos FloWorks is used the method of finite volume.

3. Solution of the problem and results

Investigation of influence of the pulsating regime of motion of hot coolant (air) on cooling process in air coolers was performed on example of a tubular heat exchanger. Section of the heat exchanger is shown in Figure 1. Hot coolant is moving along the annular gap formed by the inner and outer tubes (flow direction indicated by the arrows in Fig. 1, all dimensions in mm) with internal diameter of the ring, respectively, 34 mm and 44 mm.

Temperature of hot air at the inlet of cooler is 600°C and positive pressure is 10 bar. Required temperature at the outlet is 400°C. Air is cooled with cold coolant (water) according to counterflow scheme. The Water is moved through the inner pipe with diameter 30 mm and in the outer annular gap (Fig. 1) with internal diameters of the ring respectively 48 mm and 58 mm.
Initial temperature of water at the inlet of cooler 50°C and a overpressure 2 bar are maintained constant. Water flow rate should be such that the temperature at the outlet increased by no more than (5 - 7)°C.

Were investigated two regimes of movement of cooled air:
1) unsteady with pulsating volumetric flow rate Q(t) (Fig. 2);

2) stationary, whose flow rate Q is equal to the in time averaged pulsating flow.

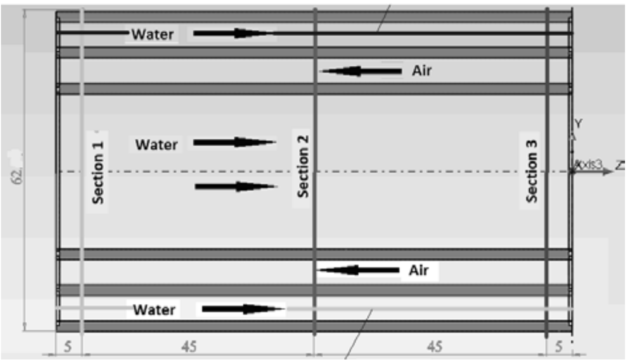


Fig.1. Section of the cylindrical model of air cooler with water cooling.

The purpose of the analysis of two regimes consists in estimating an opportunity to use results of quasi -stationary simulation data for a preliminary estimation of parameters of designed heat-exchangers variants.

Pulsating regime of change of volumetric airflow Q(t) depends on the law of variation of velocity of working piston, which push hot gas into air cooler. For known velocity of the working piston V(t) (Fig. 2) the value of the volumetric flowrate Q(t) differs from it by a constant factor. In this paper, in order that determine Q(t) it is necessary to multiply the value V(t) by $0.0001m^2$.

The dependence V(t) at the "first" half-periode of pulsating regime is modeled by means the curve that matches the positive branch of sinusoid (Fig. 2, for example. for the time, $0.2 \leq t \leq 0.25s$), and at the "second" half-periode at $0.25 \leq t \leq 0.5s$ is modeled by condition Q(t) = 0. In the works [1,2], it is shown that the speed of movement of the working piston of Stirling engine is well described by means of curves sin(ω t), where ω - angular frequency.

It was calculated temperature change (Fig. 3) in the radial direction of the annular channel with the hot air inside the sections 1, 2 and 3 (Fig. 1) at the maximum volumetric flow rate $Q_{max}=0.001m^3/s$ of pulsating and equal average and steady volumetric air flow rate $Q=0.00032m^3/s$. Volumetric flow rate of cooling water in the both tubes was the same and equal to $0.0005m^3/s$. On the outer surface of the heat exchanger was taken into account convective heat transfer to environment. Material of all tubes is steel with known thermophysical properties. Note that the Section 1in Figure 1 is located near the outlet, but Section 3 - near the inlet of the air cooler, and in Figure 3, 3b, the temperature T(K) is given in Kelvin degrees.

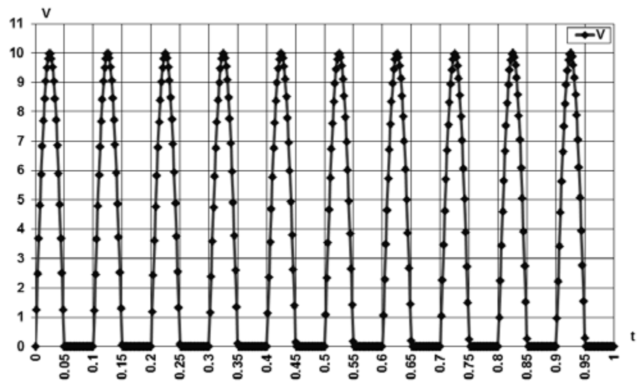
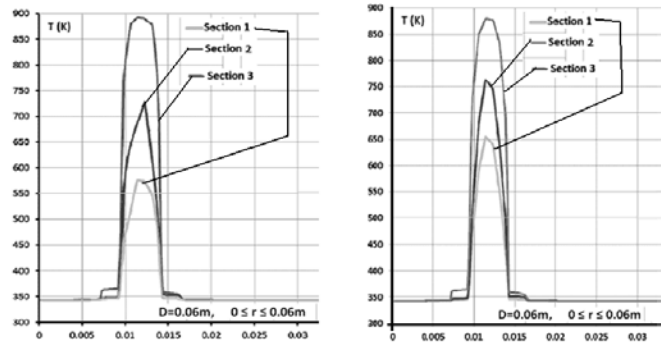


Fig. 2 Dependence of speed of working piston V m/s on time t(s).

Comparison of the results shown in Figure 3, and similar results for coolers with different geometrical and input thermal gas-dynamic parameters showed that for relatively short air coolers (the ratio of length to the overall diameter <5) with the quasi-stationary and pulsating flow of hot air is permissible to use the quasi- stationary methods for an approximate estimation of in time averaged parameters of heat exchangers.



a) b)

Fig. 3. The radial temperature distribution in the different sections of the air cooler: a) stationary regime, b) pulsating regime.

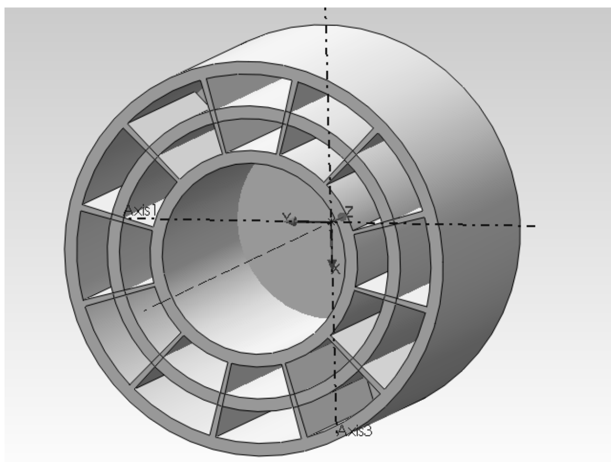
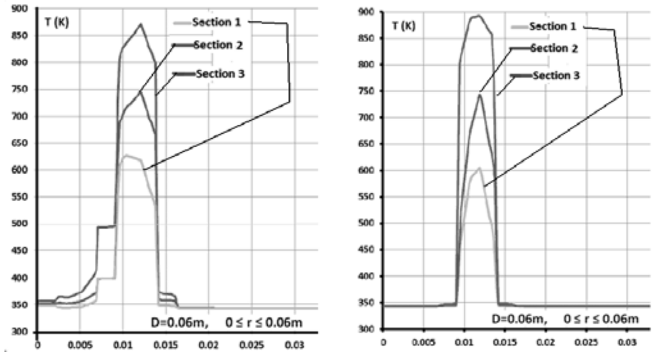


Fig. 4. Model of tubular heat exchanger with longitudinal ribs.

Impact analysis of the effect of increase of the heat transfer area on parameters of air cooler it was performed on the model of examined above tubular heat exchanger (Fig. 1), to which were added the longitudinal ribs (Fig. 4).



a) b)

Fig. 5. The radial temperature distribution in the different sections of ribbed air cooler a) stationary mode, b) pulsating regime.

Compared with air cooler without ribs, outlet temperature of air cooler with ribs has decreased approximetly by ≈ 50°C. Comparison of quasi- stationary and pulsating modes confirms the conclusion about possibility of using the quasi-stationary method for preliminary calculations

The characteristic property of the relatively short air coolers is quite a big difference of the inlet and outlet temperatures (≈ 200°C). This requires taking into account the increase the density of the air along the channel and, consequently, reduction of volumetric flow rate while respecting the law of mass conservation (conservation of mass flow Q_m). The data shown in Figure 6, are evidence of a reduction of volumetric flow rate Q(t) in the outlet section, compared with the inlet by almost at two times and confirm the need for such accounting in the calculations.

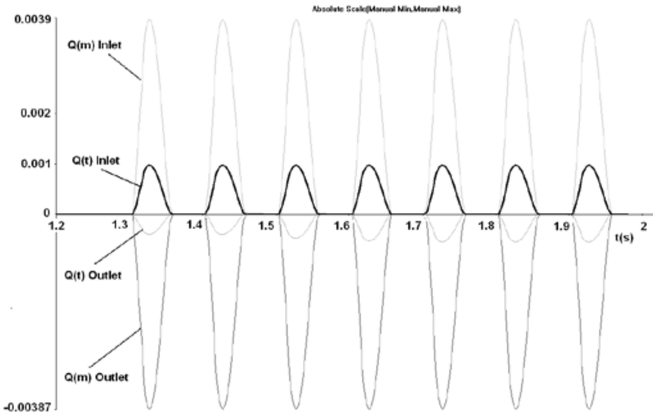


Fig. 6. Graphs of change of mass and volumetric flow rate of hot air at the inlet and outlet of ribbed cooler in pulsating regime of motion of the gas.

The most significant differences between the stationary and pulsating regimes of viscous flow in air cooler occur in case of a relatively small frequencies of oscillations of flow rate in the tube. The reason is increase (or decrease) of the hydraulic friction resistance due to change of velocity profile in the pipe section under the influence of a positive or negative acceleration of the flow. In case of the positive acceleration complete pressure diminishes along a stream, that like diminishing of pressure under act of hydraulic resistance. Consequently can appear the zones of backflow near-by the walls of pipe. At increasing of amplitude of flow rate the maximum values of local velocities moves from the axis closer to the wall of tube. For the hydraulic approximation of laminar flow of (капельной жидкости) dropping liquid with harmonic change of flow rate, this problem was studied in detail in works [5,6]. In these studies it was shown that the change of friction resistance under the influence of unsteady flow can be taken into account using thecorrection factor $\chi = 0.5\sqrt{\omega^*} + 0.4$, where dimensionless frequency $\omega^* = \omega r^2/8$, r - radius of the tube, ν - kinematic viscosity factor of the gas at a given temperature and pressure, $\omega = 2\pi n_c$ - the angular frequency of gas fluctuations, n_c - number of oscillations of the flow rate in second (see Fig. 2, n_c = 10 1/s). Estimates made for the tubular cooler with gas parameters examined in this work showed that the correction factor approximately equal $\chi \approx 14$, i.e. the friction factor can be greater than for regime of stationary flow.

A detailed analysis of the profile of a longitudinal velocity, which determines the volumetric flow rate in the annular gap of air cooler, confirms the presence of periodic backflow zones near solid walls (Fig. 7, arrows determine the direction of motion of fluid particles).

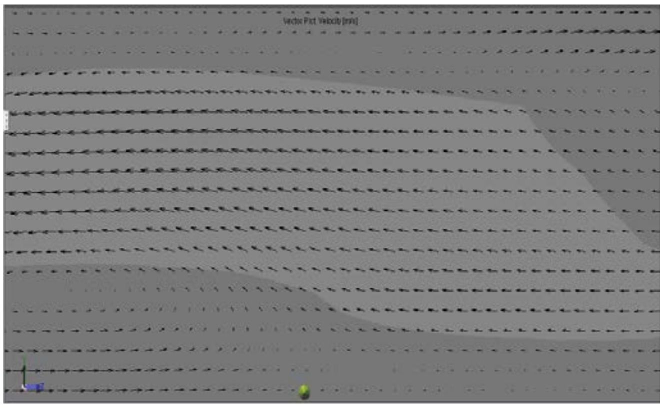


Fig.7. Area with a backflow near the walls of the annular air cooler

4. Conclusions

1. Developed the method of computer simulation and numerical calculation of the features of gas - thermodynamic parameters of models of heat exchangers of Stirling engine with a pulsating flow of working fluid.
2. Justified the possibility of using of quasi-statioanary calculation method for the approximate evaluation of time-averaged parameters of heat exchanger.
3. Numerical calculations confirmed the possibility of significant influence of relatively low frequencies of fluctuations of gas flow rate (size of order 10 *1/s*) on the shape of the longitudinal velocity profiles, as well as their significant deformation with initiation of backflow zones that are periodically arranged along the channel.

5. Literature

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Acknowledgments

This work has been supported by the European Regional Development Fund within the project "Modeling and Research of Effective Small Size Heat Engines Gas Processes", (agreement Nr.2010/0235/2DP/2.1.1.1.0/10/APIA/VIAA/093, RTU PVS ID 1536).